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THE SOURCE OF THE RELATIVISTIC PARTICLES IN THE GALACTIC CENTER ARC

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ABSTRACT

Three fields in the molecular cloud M0.20-0.033, located near the midpoint of the filamentary "Galactic center arc," have been imaged in the CS $J = 2$–1 line with the OVRO millimeter interferometer. Several molecular clumps have been found to coincide with the endpoints of a number of the arc's nonthermal filaments (NTFs), suggesting that the relativistic particles present along the filaments originate in these molecular cloudlets. The most striking correlation involves a clump that is elongated along the direction of a pair of NTFs, and that approximately coincides with both their endpoints. These observations thus provide clues to the particle acceleration mechanism operative in the Galactic center arc: magnetic energy is likely liberated as the ambient field, tangled by the clumps' motions, reconnects in the advancing clumps' leading, externally ionized, surface layers.

Subject headings: galaxies: nuclei — Galaxy: center — ISM: molecules

1. INTRODUCTION

Surely one of the most intriguing phenomena to be found anywhere in our Galaxy is the 30 pc–long sheaf of magnetized plasma filaments which cuts across the Galactic plane near the center of our Galaxy (Yusef-Zadeh, Morris, & Chance 1984). This "Galactic center arc" shows strongly polarized radio continuum emission (Seiradakis et al. 1985; Tsuboi et al. 1986; Yusef-Zadeh & Morris 1987b), with no line emission (Yusef-Zadeh, Morris, & van Gorkom 1989), consistent with a synchrotron origin, and implying the existence of both a strong magnetic field ($\boldsymbol{B} \sim 1$ mG) directed along the nonthermal filaments (NTFs), and an efficient generation mechanism for the relativistic particles radiating along the filaments. While various models have been considered for the production of relativistic particles and their organization into filaments, none yet has a firm observational basis (e.g., Sofue & Fujimoto 1987; Benford 1988; Heyvaerts, Norman, & Pudritz 1988; Morris & Yusef-Zadeh 1989; Serabyn & Güsten 1991).

Important clues to the nature of the NTFs have been provided by the discovery of a molecular cloud (M0.20-0.033 or the "25 km s^{-1} cloud") near the arc's midpoint (Lasenby, Lasenby, & Yusef-Zadeh 1989; Serabyn & Güsten 1991, hereafter SG). The CS $J = 3$–2 map of this cloud from SG, reproduced in Figure 1 (Plate L5), shows that this cloud's most prominent emission ridge, which extends approximately along the Galactic plane, closely follows the anfractuous H II region G0.18-0.04 (the "sickle"; Yusef-Zadeh & Morris 1987a, hereafter YZM), and agreement between molecular and ionized velocities implies that G0.18-0.04 represents the ionized surface of M0.20-0.003 (SG). Moreover, as the sickle appears to "wrap around" (in projection) the sheaf of nonthermal filaments making up the arc (YZM), this nonthermal gas is likely also associated with G0.18-0.04/M0.20-0.033. Further morphological evidence for an intimate interaction between the thermal and nonthermal structures is presented by YZM, and some sort of interaction of molecular and nonthermal gas is suggested by curious molecular "protrusions" from M0.20-0.033, which seem to line up along the direction of the NTFs (SG). By virtue of M0.20-0.333's broad line width, 15–20 km s^{-1}, which is typical of Galactic center molecular clouds (Güsten 1989), the entire M0.20-0.033/G0.18-0.04/arc complex can then be located within ~ 150 pc of the Galactic center (SG).

As suggested by YZM and SG, G0.18-0.04 likely represents the interaction zone between a hapless Galactic center molecular cloud and the magnetic fields and energetic particles present in the arc. However, it is not known if the arc's relativistic particles predate the arrival of the molecular cloud in its vicinity (e.g., YZM), or if processes at work in the molecular cloud itself generate the copious high-energy particles (Heyvaerts et al. 1988; Benford 1988; SG). Thus, to harvest the information contained in the molecular gas component near the sickle, we have imaged several fields near the G0.18-0.04 interaction zone with the OVRO millimeter-wave interferometer during the winter 1989–1990.

2. OBSERVATIONS AND RESULTS

In order to discriminate against foreground emission from diffuse Galactic disk gas, M0.20-0.033 was observed in a molecular transition which requires high densities ($\sim 3 \times 10^4$ cm^{-3}) to excite—the CS J = 2–1 line at 97.981 GHz. Because the cloud's full extent is more than 5′ × 3′ (Fig. 1), while at 98 GHz the OVRO primary beam is only 74″ FWHM, this initial study included only a small fraction of M0.20-0.033. Three promising fields were chosen on the basis of the single-dish CS $J = 3$–2 map (Fig. 1). Two of the fields, centered near molecular peaks located at points of intersection of the NTFs with the H II region, encompass much of that part of G0.18-0.04 that extends along the Galactic plane. The third field, centered on a curious extension of M0.20-0.033 along an NTF (SG), has little or no associated thermally ionized emission (Yusef-Zadeh et al. 1989).

With three telescopes in five configurations, and baselines up to 60 m E-W and 80 m N-S, the synthesized beam was 7″.5 × 9″.3 FWHM ($\alpha \times \delta$). Each track was shared among the three field centers and the phase calibrator, NRAO530. The passband was calibrated on 3C 273, and the flux on Mars. The spectral data were acquired with two sets of 32-channel filterbanks, both centered at an LSR velocity of 20 km s^{-1}, with channel widths of 5 and 1 MHz, respectively. In the 5 MHz data, most of the line flux is contained in 1–2 channels. The

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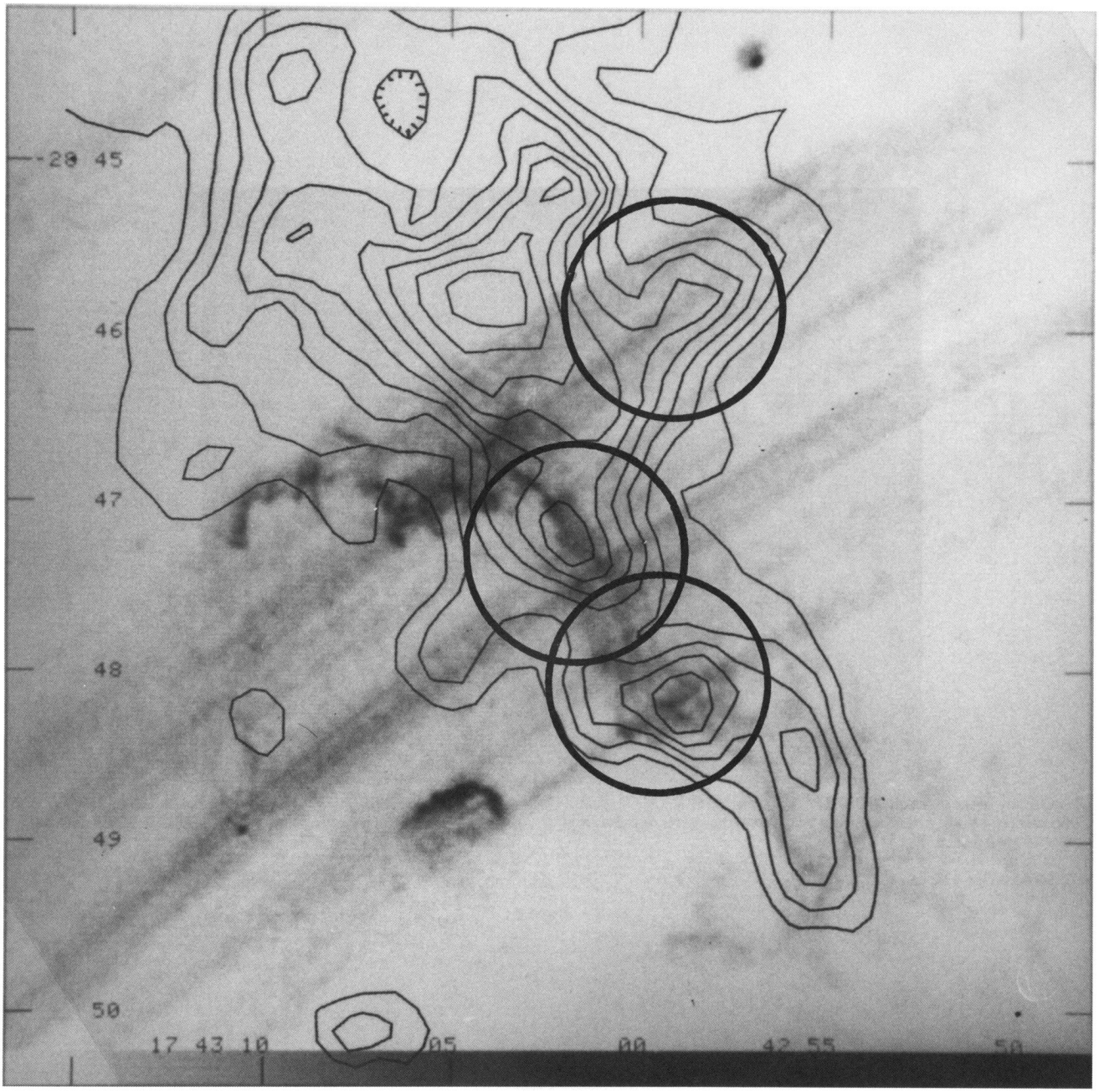

FIG. 1.—Overlay (from SG) of single-dish CS $J = 3$–2 contours and 5 GHz continuum radiograph, showing the three fields imaged at OVRO. l increases toward P.A. $\sim 30°$, while b is $\sim$parallel to the NTFs. As discussed in SG, several protrusions from the molecular cloud along the direction of the NTFs seem to be present, which we list here for purposes of inspection. In terms of (α, δ) coordinate pairs (1950), they are located roughly at (17:42:59, −28:45:50), (17:43:05, −28:48:00), (17:43:02.5, −28:45:10) and possibly also at (17:43:11.5, −28:46:00).

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1 MHz data resolve the line spectrally, but, with one exception, little additional information is present, as the channel maps tend to reflect intrinsic line widths (~ 15 km s^{-1}) rather than spatial gradients.

Figure 2 (Plate L6) shows an overlay of the mosaicked 5 MHz CS 2–1 data on the 5 GHz radiograph of YZM. In order to include all of the interferometrically detected emission with maximum S/N, only velocity channels with substantial emission were included: the two outer fields thus include only the first channel redward of center, while the central field sums the flux from the two central channels. The detected emission originates primarily in one or two distinct molecular clumps per field, with a size range of 10″–45″ (or ~ 0.4–2 pc for a distance of 8.5 kpc). The detected structures are more compact than the single-dish map (Fig. 1) suggests, and also much less extended (at least in one dimension) than the OVRO main beam, implying that much of the observed difference can be attributed to increased resolution. The molecular gas in M0.20-0.033 is thus very highly clumped, with typical clump masses of $10^3\ M_\odot$. A comparison of the peak observed radiation temperatures, 2–3 K, to single-dish spectra implies that $\lesssim$ half of the single-dish flux is seen interferometrically. The remainder presumably arises in a more diffuse interclump medium (seen linking the clumps in Fig. 1). In the following, the observed CS clumps will be referred to, in the south to north order of the fields, as CS1 (E and W), CS2, and CS3. Only CS1-W shows any velocity structure (Fig. 3), with a velocity gradient of ~ 0.7 km s^{-1} arcsec^{-1}.

Figure 2 reveals a close correlation of molecular material with the H II region G0.18-0.04. Furthermore, it also shows one striking correlation of molecular and *nonthermal* gas: clump CS3 abuts two of the NTFs approximately where they fade from view and is also elongated along their direction. The fact that this molecular clump lies near the terminations of these NTFs provides evidence for a direct relationship between these two gas components. Although not as immediately obvious, correspondences of NTFs with other CS clumps also exist, and in general the map suggests that the CS clumps tend to lie directly athwart one or more of the NTFs. Conversely, the NTFs seem to cross G0.18-0.04 selectively near the locations of the CS clumps (albeit some tangentially rather than directly), a curious coincidence, given that the observed clumps occupy only a small area.

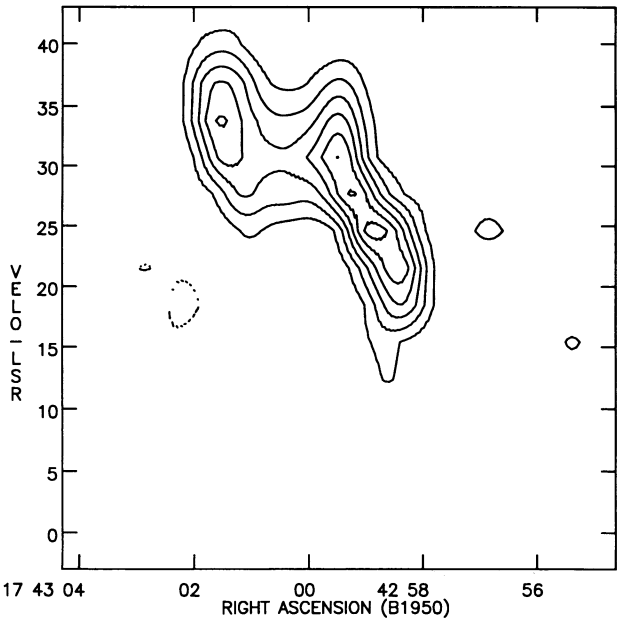

FIG. 3.—Right ascension–velocity plot through clumps CS1E (*left*) and CS1W (*right*) at declination (1950) = −28:48:09.7. The contour levels are in steps of 0.35 Jy beam^{-1} and the peak flux is 2.4 Jy beam^{-1}. CS1W shows a velocity gradient of ~ 0.7 km s^{-1}arcsec^{-1}, or 17 km s^{-1} pc^{-1}.

We now examine these spatial coincidences systematically (keeping in mind the possible effects of projection and observer subjectivity), using the NTF numbering scheme of YZM. In order of increasing l, the first filament, I (lower right in Fig. 2), is seen to cross clump CS1-W. This occurs close to the point at which this filament bends by $\sim 5°$ (YZM). Filament I also crosses a south-facing "bay" in the molecular material below CS1-E. Next, filament II crosses clump CS1-E tangentially, approximately where this NTF fades from view. A gap in molecular material follows, matched by a gap in the NTFs. Clump CS2 then spans the distance between filaments III and VI. In projection, these two filaments only graze the opposite edge of CS2, but filaments IV and V cross CS2 directly. Note, however, that filaments III, V, and VI all fade noticeably near CS2. The next filaments are the close pair VIIA and B, both of which fade in intensity near CS3: VIIA in line with the clump, and VIIB as it seemingly grazes along this clump's edge. The final filament, VIII, may be linked to molecular peak 2 of SG, which it crosses (Fig. 1), but our interferometer fields do not include this region.

Although projection effects leave room for uncertainty, the data in hand nevertheless suggests that a dense ($n \sim 10^5$ cm^{-3}; SG) molecular clump is present along each individual NTF, intimately associated with it. Generalizing, the NTFs might actually occur in small subgroups, with each subgroup related to a separate molecular clump. If so, the mysterious endings and bendings of the NTFs near G0.18-0.04 (YZM) can likely be clarified as due to interactions between the NTFs and the detected molecular clumps. These interactions may not be uniform in nature, as the different molecular clumps show different morphologies: CS3 is elongated along its associated NTF, while the other clumps are not. However, although the exact morphological relationships between individual molecular clumps and NTFs may vary, the basic correspondence between them already has far-reaching implications. In particular, since the NTFs tend to terminate on, or near, molecular clumps (and allowing for more extended flux resolved out interferometrically, these two cases are likely the same), this allows for only two alternatives: the detected molecular clumps must be sites where the relativistic particles in the arc are either generated, or absorbed.

3. DISCUSSION

One can distinguish between these alternatives with existing observations. First, we note that G0.18-0.04 is located near the true Galactic plane, where the NTFs are well defined. Farther from the Galactic plane, the NTFs splinter and become more diffuse (Yusef-Zadeh & Morris 1987b), and finally merge into amorphous plumes of gas extending far above and below the Galactic plane (Seiradakis et al. 1985; Tsuboi et al. 1986), with only one or a few remaining faint filaments (e.g., Yusef-Zadeh & Morris 1988). Thus, the entropy of the arc appears to increase with distance from the Galactic plane. The emitted synchrotron spectrum also steepens with increasing distance from the plane, from, at small b, the $\nu^{0.3}$ spectrum character-

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PLATE L6

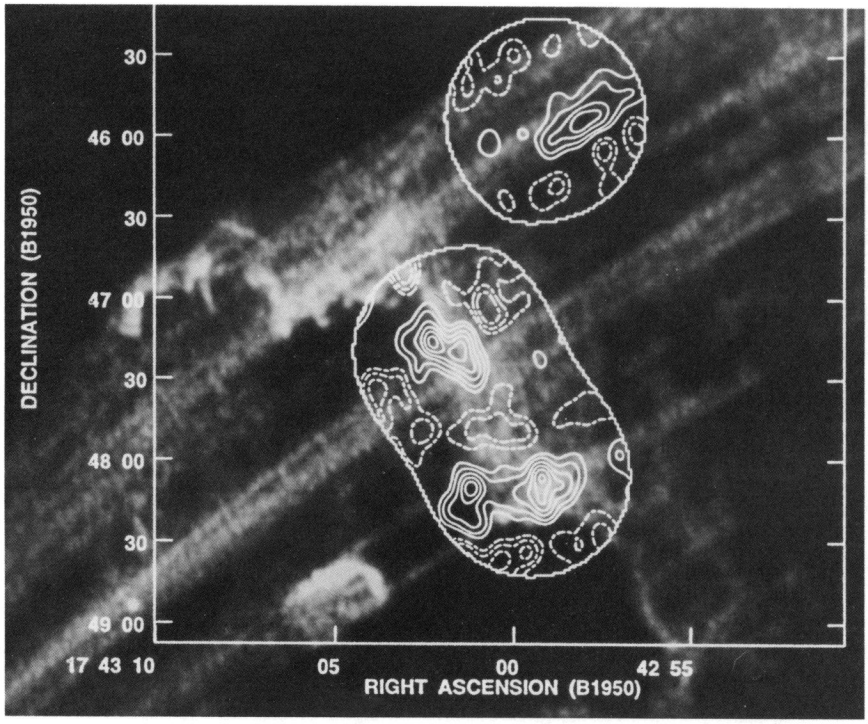

FIG. 2.—Overlay of the mosaicked OVRO 5 MHz filterbank CS $J = 2$–1 data on the 5 GHz radiograph of YZM. The two other fields show only the first channel redward of center (20 km s^{-1}), but the central field shows the sum (not average) of the flux from both central channels. The contour levels for the CS emission are 1.5, 3, 5, 7, 9, 11 × 100 mJy $beam^{-1}$.

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istic of a monoenergetic, and hence young, electron population (Reich et al. 1988), to a much steeper spectrum in the plumes, indicative of a more geriatric electron population (Reich 1990). Both effects imply that the arc's energy source lies near the Galactic plane. The detected molecular clumps, on which the nonthermal filaments are observed to terminate, must then be the source, rather than the sink, of the arc's relativistic particles. The more diffuse nature of the distant plumes can then be attributed to their escape from high confining pressures near the Galactic plane.

What then accelerates the initially thermal gas in M0.20-0.033 to relativistic energies? It is generally agreed that the high magnetic field, $\boldsymbol{B}$, plays a role, and Heyvaerts et al. (1988), Benford (1988), and SG discuss models in which molecular clouds interact with high-$\boldsymbol{B}$ fields to accelerate particles to high energies. However, the proposed models differ substantially in detail: Heyvaerts et al. (1988) and SG consider field reconnection caused by the impact of a magnetic flux tube with a molecular cloud, while Benford (1988) and Morris & Yusef-Zadeh (1989) discuss inductive acceleration caused by the motion of a partially ionized molecular cloud relative to the ambient field. As the Petschek reconnection mechanism (Heyvaerts et al. 1988; Blandford 1993) implies an electric field of $\sim 10^{-5}$ V cm^{-1}, the acceleration to $\sim$GeV energies (Sofue, Murata, & Reich 1992) takes place on scales too small to be observable ($\sim 10^{14}$ cm).

Are there then any observable effects on M0.20-0.033 due to the arc's high-$\boldsymbol{B}$ field? As this cloud's main ridge is oriented roughly along the Galactic plane, its large-scale structure is likely dominated by gravitational forces. However, as suggested by the presence of several molecular protrusions from M0.20-0.033 along the direction of the NTFs (SG; Fig. 1 caption), the field may affect the small-scale structure of individual clumps. While some of these identifications of field-aligned structures may be subjective, and studies of molecular clouds in the disk of the Galaxy find no unique relationship between field direction and cloud elongation (e.g., Goodman et al. 1990), clump CS3 clearly lines up with an NTF (Fig. 2), suggesting that pressure due either to the $\boldsymbol{B}$ field, or to relativistic particles plays a role in this clump's elongated morphology. However, because of the low particle luminosities in the NTFs (see below), the pressure of the relativistic gas is negligible ($\sim 10^{-13}$ ergs cm^{-3}). Rocket effect pressure (from surface ionization) can also be ruled out, at least for CS3, because this clump has no associated H II component. Thus, we conclude that the alignment of CS3 along the NTFs likely provides a good candidate for a magnetically aligned molecular cloud structure: as magnetic pressure acts only perpendicular to the field lines, the presumably partially ionized clump is compressed laterally by the field, permitting flow of cloud material only parallel to the NTFs. For equipartition with the cloud's turbulent pressure of $\sim 10^{-7}$ ergs cm^{-3}, the required $\boldsymbol{B}$ field is a few mG (the agreement with earlier $\boldsymbol{B}$ field estimates based on ram pressure arguments is fortuitous, as the densities assumed were lower by an order of magnitude, which compensated for the higher assumed bulk velocities). Finally, we note that as one of the candidate NTF-aligned protrusions in Figure 1 lies outside the region of the NTFs, it is possible that magnetic pressure is also important beyond the region of the NTFs. This would considerably weaken the case for any model based upon an isolated flux tube coincident with the arc, as in, for example, Tsuboi et al. (1986), Yusef-Zadeh & Morris (1987b), Heyvaerts et al. (1988), and SG.

However, does the magnetic field have sufficient energy to power the arc? High-energy particle production is a familiar problem from solar and planetary magnetospheric research, and for the electrons the dominant process is likely to be electrostatic acceleration during the reconnection of oppositely directed $\boldsymbol{B}$ fields (Forman, Ramaty, & Zweibel 1986). This process likely proceeds via turbulent mixing of the ambient and clump fields on the surfaces of the detected CS clumps, as suggested by Heyvaerts et al. (1988) and SG. Given a clumpy molecular cloud advancing with a large relative velocity through an ambient $\boldsymbol{B}$ field, the field internal to the clumps, being tied to the partially ionized medium, is dragged along, while the external field is compressed and parted by the ram pressure of each of the passing clumps. The velocity gradient across CS1-W (Fig. 3) indicates that clump rotation may also twist the field. Thus, field reversal across clump boundries is expected to occur, leading naturally to reconnection (Parker 1979; Zirin 1988). However, although diffusive timescales are shorter in a neutral cloud, reconnection in a predominantly neutral cloud is unlikely to be an effective way of accelerating the few available electrons to relativistic energies, because of dissipation in collisions with neutrals. The H II region G0.18-0.04 implies an abundant source of free electrons, and we infer that the existence of a mechanism for ionizing the cloud surface (see below) is probably essential to the efficacy of the acceleration process.

After acceleration, the high-energy particles attach themselves to the nearest vertical field lines and spiral away from their origin with an undetermined bulk velocity. As suggested by the variety of filament-clump interactions seen, the electrons may be able to depart to one or both sides, the choice likely determined by the topology of the local clump/field interface. As only field lines near a clump "hot spot" can then be "lit up," the most prolific reconnection sites must then be situated on the clumps located at the origins of the brightest NTFs. However, more diffuse synchrotron emission also fills the region between the filaments (Lesch & Reich 1992), which can be explained via lower level recombination occurring in the more diffuse interclump molecular medium (observable in Fig. 1 by virtue of the continuous H II and CS emission spanning the length of G0.18-0.04). Reconnection in a clumpy molecular medium thus accounts for both the multiplicity of NTFs, and the more diffuse halo of synchrotron emission surrounding them, even in an *uniform* vertical magnetic field. Thus, attribution of the multiplicity of NTFs to the multiplicity of parent molecular clumps avoids the uncomfortable assumption of high-contrast magnetic flux tubes (e.g., Heyvaerts et al. 1988), which would imply large gradients in magnetic pressure.

Theoretically (Parker 1979; Hassam 1992), reconnecting fields approach each other at a velocity in the range $2V_A/R_m$ to $V_A/\ln(R_m)$, where V_A is the Alfvén speed and R_m is the magnetic Reynolds number, the choice being governed by the topology of the fields. Observationally, reconnection is found to proceed at the faster rates (Parker 1979; Zirin 1988; Blandford 1993), being usually in the range $(10^{-2}$ to $10^{-1})V_A$. The observed molecular (SG) and ionized (YZM; Simpson et al. 1990) densities, $\sim 10^5$ cm^{-3} and 10^3 cm^{-3}, respectively, bracket the Alfvén speed in the range 10–100 km s^{-1}. Since the clumps convectively sweep aside field at $\sim$25–100 km s^{-1} (depending on their true three-dimensional motion relative to the field), the expected energy conversion for field reconnection lies in the range 10^{-3} to 4×10^{-1}.

To compare to the actual efficiency, we consider the arc's

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energy content. The NTFs' nearly flat centimeter-wave spectra (YZM; Inoue et al. 1989), and their nondetection at 43 GHz (Sofue et al. 1992), imply that each individual NTF emits ~ 1–4 $L_\odot$, and all the NTFs combined $\sim 30\ L_\odot$. As the diffuse halo of emission surrounding the NTFs has a larger solid angle, and is still observable at 43 GHz (Sofue et al. 1986), its luminosity dominates, but is still only $\sim 100\ L_\odot$. The rate at which magnetic energy is swept up by the cloud's motion easily exceeds this, being $\sim 2 \times 10^3$ to $3 \times 10^4\ L_\odot$, for $\boldsymbol{B} \sim 1$ mG, a cloud-field relative velocity of 25–100 km s^{-1}, and a cross-sectional area of 10 pc^2. The implied conversion efficiency of $\sim 3 \times 10^{-3}$ to 5×10^{-2} falls within the theoretical range estimated in the preceding paragraph, implying that field reconnection can easily account for the arc's synchrotron luminosity.

However, the total FIR luminosity of the G0.18-0.04/M0.20-0.033 interface region is some $10^6\ L_\odot$ (Morris et al. 1993), well above the level the magnetic field is capable of providing, and far above the arc's synchrotron luminosity. As implied by IR fine-structure line intensities (Simpson et al. 1990; Krenz et al. 1994), the dominant energy source for ionizing and heating the cloud surface is likely to be UV radiation from OB stars, rather than Alfvén's critical ionization effect (Morris & Yusef-Zadeh 1989; SG). However, molecular clouds illuminated by O stars do not normally produce copious relativistic particles, and so, as the swept-up magnetic energy is easily sufficient to power the arc's nonthermal luminosity, the magnetic field remains the most viable energy source for particle acceleration. As the ionization of the cloud surface can be viewed as merely providing a source of electrons for acceleration, the origin of the ionization, whether magnetic or radiative, does not alter the preceding discussion.

However, one important question remains: how can one account for the arc's uniqueness? Although a few other isolated filaments occur near the Galactic center (e.g., Anantharamaiah et al. 1991), the multiplicity of NTFs in the arc remains unique. This is striking in view of the fact that the individual model ingredients discussed, that is, molecular clouds, high-$\boldsymbol{B}$ fields, and H II regions, all occur elsewhere in the environs of the Galactic center. We next argue that a cloud orbiting at a large relative velocity to the field, together with a nearly head-on ionizing source, may combine to determine the rarity of the observed phenomena.

A large relative velocity between the cloud and field is a necessary condition for a high rate of sweeping-up flux, or for "accessing" the magnetic energy. Surface ionization is required to provide free electrons, but the rarity of "arcs" implies that this alone is not a sufficient condition. To arrange for reconnection, the magnetic field must first be deformed. Here surface ionization plays a second role, as the ease of passage of a molecular cloud through an external field is determined by the distribution of the ionized component. If a surface tangent to a cloud's trajectory were ionized, the cloud could easily shear, whereas if a cloud's leading surface were ionized, its passage through the external magnetic field would be resisted much more strongly (although not enough to slow the cloud in less than an orbital time). The breaking of the cloud's front surface would lead directly to turbulent mixing of the magnetized cloud layers with the external medium, generating neighboring regions with reversed fields in the process. While turbulent mixing is likely at work in M0.20-0.033, the shearing case may apply to the molecular clouds associated with the nearby arched filaments (Serabyn & Güsten 1987; Morris & Yusef-Zadeh 1989), which show only a single isolated NTF in their vicinity (if our suppositions are correct, this filament should also be associated with a dense molecular clump).

We thus conclude that the best model to explain both the acceleration of particles to high energy in the arc, and the uniqueness of this phenomenon, is based on a molecular cloud orbiting obliquely through a region of high $\boldsymbol{B}$, while at the same time its leading surface is ionized through an encounter with UV radiation. This scenario actually relies on individual processes which can occur anywhere in the Galaxy, but outside of the Galactic nucleus, the weaker magnetic field and the usually small relative velocities between clouds and ambient field lines presumably make an arclike event next to impossible.

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